Make accurate temperature measurements using semiconductor junctions

Sachin Gupta and Umanath Kamath, Cypress Semiconductor

6/20/2012 10:02 AM EDT

There are numerous sensors available for temperature measurement under the name thermal sensors. Popular ones are the thermistor, thermocouple, RTD. Diodes can be used to sense temperature due to the change in their forward voltage with change in temperature. One of the advantage of using diodes is they have a nearly linear relationship between temperature and voltage applied. Diodes are being used extensively in integrated circuits to measure the die temperature but now are not limited to that.

Diodes are the most inexpensive among all the temperature sensors and are the likely candidate to be selected in low cost applications. Understanding of the characteristics of diode junction as a function of temperature is important for accurate measurement. Although diodes are not as accurate as other sensors like thermocouple, they provide reasonable accuracy, which makes them usable in lot of low precision applications. This article talks about the fundamentals of diode's forward voltage and steps to make accurate temperature measurements using them.

The fundamentals of operation

First, let's look at the fundamentals involved.

Equation 1 (known as the diode equation) gives the current flowing through the diode when it is forward biased.

$$I = I_S e^{V/\eta V_T} \text{ – } \textbf{Equation 1}$$

Where I_S is the reverse saturation current, V is diode's forward voltage drop, η is ideality factor (a constant which has value from 1 to 2) and V_T is the thermal voltage of diode which is given by equation 2.

$$V_T = kT/q \text{ - } \textbf{Equation 2}$$

T is the absolute junction temperature in Kelvin, q is the electron charge ($1.602*10^{-19}$ C) and k is the Boltzmann's constant:

$$(1.38*10^{-23}\ \mathrm{J\ K^{-1}})$$

Before we dive into the electronics of measuring the temperature, let us look into the mathematics to get temperature from these equations.

If two known currents (I1 and I2) related by I2 = N * I1are passed through diode, forward current will be given by the following equations respectively.

$$I_1 = I_S e^{V_1/\eta V_T} \text{ - } \textbf{Equation 3}$$

$$I_2 = I_S e^{V_2/\eta V_T} \text{ - } \textbf{Equation 4}$$

After dividing equation 4 by 3 and manipulating, it yields equation 5.

$$T = q(V_2 - V_1)/(k\eta \ln\left(\frac{I_2}{I_1}\right))$$ - **Equation 5**

In this equation, K, η, q are constants as discussed before. I1 and I2 are the known currents that were passed though diodes. V1 and V2 are the measured voltages across diode. Hence the temperature can be found easily.

Now, let us focus on how to implement this. Figure 1 deals with the basic analog front end needed for such an application.

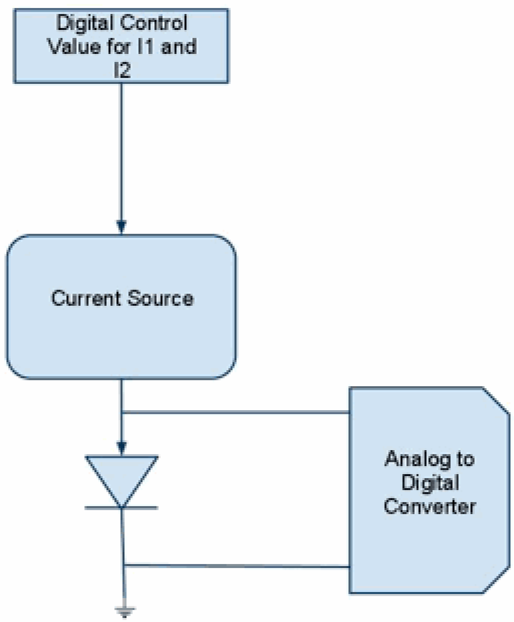

Figure 1: Sensing of the diode forward voltage

As shown in figure 1, a programmable current source is used to set a particular current flowing through the diode. Voltage excitation is not used because it will add error in measurement due to wire resistance or trace resistance and due to routing resistances inside the device itself. The drop across the diode is later fed to an ADC, which then converts to digital value. In equation 5, if we substitute the value of N as 10 and η as 1, for 1 ^{o}C change in temperature, sensor produces the voltage about 200 uV. To achieve it, ADC should have resolution of 20 bits with an input range of approximately 2V.

Figure 1 shows the very basic implementation and does not show the different resistances coming in the path, which can add significant error to the measurement. In diode based temperature measurement system, generally diodes sit on the far end to sense the temperature at the remote location. Excitation to different sensors (connecting the sensors to current DAC's output) is controlled using the analog MUX. The output of sensors to the ADC is controlled using analog MUX if they are taken from outside or directly to the ADC if routed internally as in case of figure 2.

Today, SoCs available in market have on chip DAC, ADC and analog multiplexers to realize whole system in a single chip. But even in these devices, resistance of internal switches, which are used for routing, should not be overlooked.

Figure 2 shows the various resistances, which come into routing and can result in significant source of error if ignored.

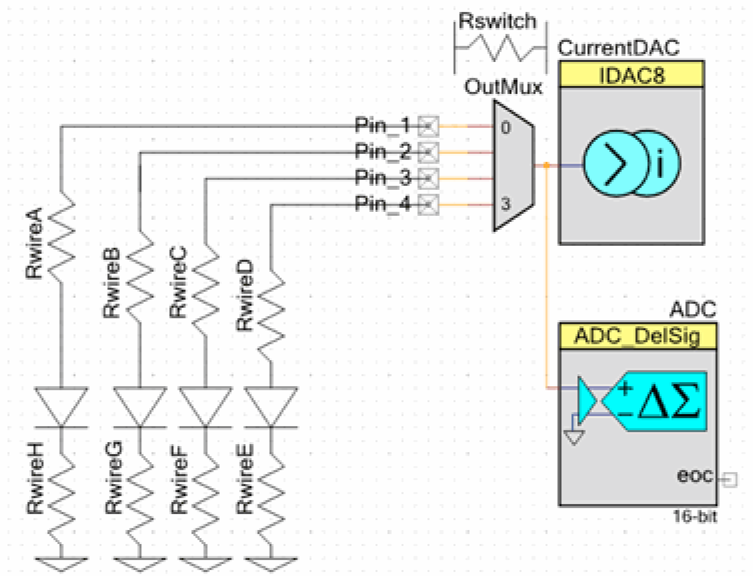

Figure 2: Different resistances in the measurement system

If we look at figure 2, there are some internal routing resistances (R_{switch}) inside the device itself (due to the switches which come into path to route the output of an on chip peripheral to a particular pin) or external if external MUXes are used. There is another component of resistance that is introduced outside the device due to wires' resistance used to connect measurement system to the diode. So, there are few important points, which should be taken care of:

Do not route the output of IDAC directly to the positive terminal of ADC internally in the device though device has capability to do it. Because it will measure voltage not just across the diode but across all the routing resistances as well. Wires running from sensor to the ADC should be connected very close to sensor pins.

Do a differential measurement. Single ended measurement will have issues due to ground offset as return path of excitation circuit also have significant lead resistance. Another advantage of differential measurement is, common mode noise, which gets coupled on the wires running parallel from diode to the ADC, does not affect the measurement, as differential voltage is still same.

Based upon the above-mentioned points, Figure 3 shows the 4-wire implementation of sensor interface (only one sensor is shown for the sake of reducing complexity) to deal with the wire resistance.

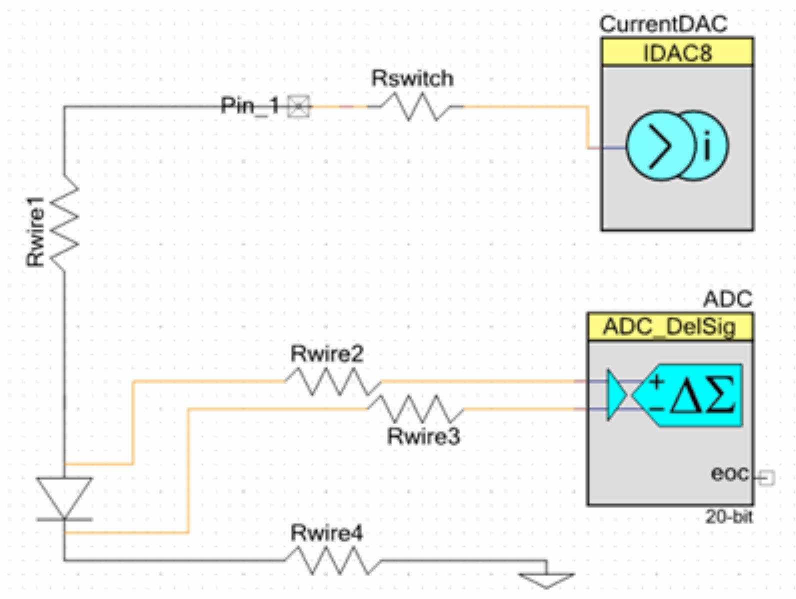

Figure 3: 4-wire measurement

In the implementation shown in Figure 3, all the unwanted resistances get avoided and only the voltage across diode is measured. At first thought one may think about the resistance, which is coming in path from sensor output to the ADC. This thought is valid if ADC has low input impedance. So, it is needed to make sure that there is some buffer (source follower) introduced between the ADC and sensor if ADC has low input impedance to minimize the leakage current and hence the error in measurement due to wire and routing resistance. SoCs, for instance PSoC3 and PSoC5 devices have ADC with an embedded buffer, which prevents such issues and need for external components in the signal acquisition path.

As can be seen from before, two known currents should be fed through a diode and a ratio metric measurement is done. In such a case, DAC's gain error will not play a vital role as long as gain error curve is linear. But it is not true for any practical DAC; actual current ratio will be different from the ideal value. This results in value of N to be N_{error} causes an error in calculated temperature.

Using equation 5 and substituting different instants, we can find that error as given by equation 8.

$$T_{ideal} = q(V_2 - V_1)/k\eta\ln(N)) \text{ - } \textbf{Equation 6}$$

$$T_{error} = q(V_2 - V_1)/k\eta\ln(N^{err})) - \textbf{Equation 7}$$

$$Error = T_{ideal} - T_{error} = T_{ideal}(1 - (\ln N)/(\ln N^{err})) \text{ - } \textbf{Equation 8}$$

So first, DAC should be calibrated to make a valid measurement. This can be done by connecting the DAC's output to a known value accurate resistance and measuring the voltage across it. In this application, only two points calibration is sufficient as only two values are of interest (I1 and I2). Ratio of the voltage read across resistance gives the actual value of N. Though, ADC should be calibrated first for gain and offset error before it is used to calibrate the

DAC as discussed later in the article. DACs also have zero scale error (offset), which also will be taken care by two-point calibration done for gain error.

Ideality factor of the diode is the next concern when it comes to the error in measurement. If ideality factor is assumed to be $\eta_{assumed}$ and actual ideality factor is η_{actual}, it will cause error in measurement. In this case, measured temperature will be given by equation 9.

$$T_{measured} = \left(\frac{\eta_{assumed}}{\eta_{actual}}\right) T_{actual}$$ **- Equation 9**

So, based upon the deviation of η_{actual} from $\eta_{assumed}$ error in the measurement will be as given in figure 4. As $T_{measured}$ is directly proportional to T_{actual}, error becomes very high at high temperatures.

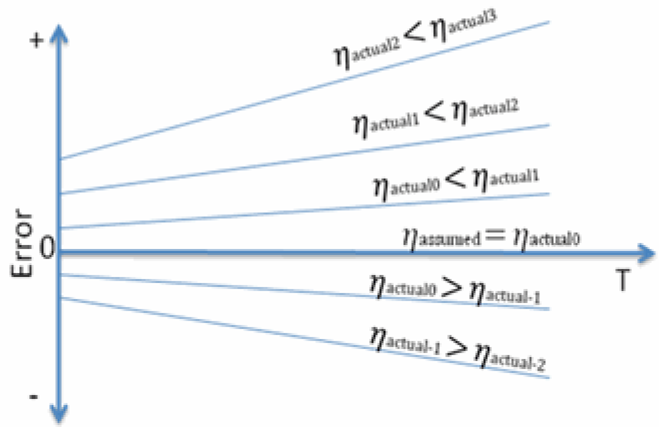

Figure 4: Temperature vs measurement error for different value of η_{actual}

Ideality factor varies (from 1.2 to 1.5) in case of diodes. Diode connected transistors on the other hand have ideality factor close to 1.004. So, transistors should be used for better accuracy. The transistor is used in diode mode by connecting the base and collector together as shown in Figure 5.

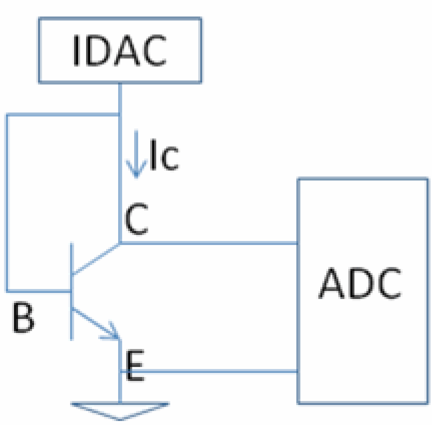

Figure 5: Diode connected transistor

While using transistors, another point to be looked at is it's current gain (h_{FE}). h_{FE} is a function of collector current (Ic)(temperature as well but it can be ignored as ratio of two voltages will cancel out this effect). It causes the ratio of

collector currents being different than the forced emitter currents and hence the error in measurement. So, to avoid/minimize this error, the transistor, which has low variation of h_{FE} over collector current, should be selected. Also, value of I2, I1 should be selected in such a way that ratio of their corresponding current gain is 1 or very close to it. Transistors' datasheets provide h_{FE} verses collector current graph which can help in making a selection. Figure 6 shows the h_{FE} vs collector current graph taken from the datasheet of 2N3904 by Fairchild Semiconductor.

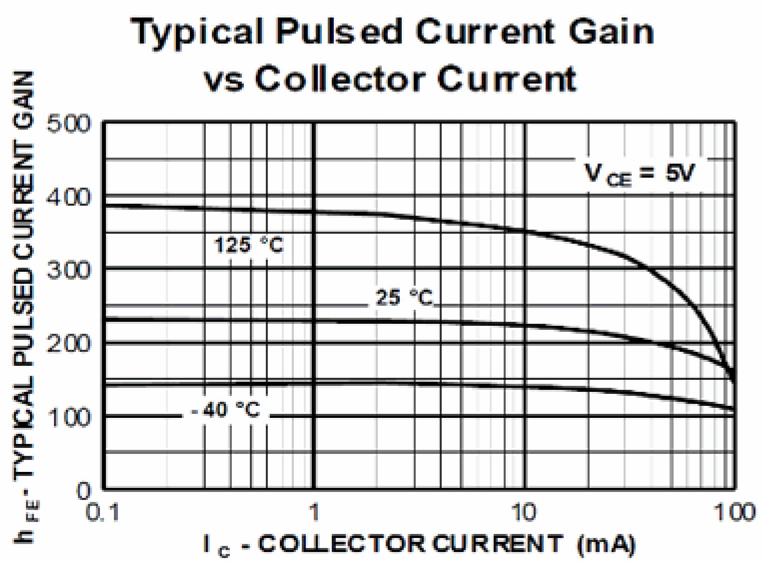

Figure 6: h_{FE} vs I_c at different temperatures

Next we need to look at the errors due to the digitization of the voltage signal using the ADC, which are the offset error and gain error. ADC's input offset voltage results in a constant value added to its output. Moreover, offset of ADC has a drift over temperature. Correlated double sampling (CDS) can be used to eliminate the offset error and offset drift with temperature. In CDS, first zero-referenced offset is measured (to measure it, both inputs are shorted and grounded which can be done using analog MUX) and then voltage across the sensor is measured. Zero reference voltage is subtracted from the voltage measured across the sensor to get the actual voltage developed across the sensor. Though offset can be dealt with by following above mentioned steps as long as it comes to making accurate measurement, but it reduces the ADC's usable input range. To avoid it, ADC in PSoC3 and PSoC5 devices have internal offset correction registers that can lower the offset to as low as 1.95uV at 20 bit avoiding the need of CDS. However, CDS still stands good to deal with offset drift and low frequency noise.

ADCs also possess gain error as in the case of DAC. To calibrate an ADC, there should be at least two accurate references in the system, which can be routed to ADC and a two-point calibration can be done. Two points calibration will assume gain error to be linear and stands good when it comes to calibration overhead (due to multipoint calibration) versus accuracy. Output of the ADC should be scaled as per the slope of the ADC output as per calibration.

High frequency noise is another source of error in measured value. When diodes are sitting at remote location connected using long wires, it is very much susceptible to the noise. Long wires act like antenna. To avoid noise pick up, twisted pair wires should be used to reduce the effective length of antenna. Wires used for excitation should be paired together and wires used for voltage measurement should be routed together. If noise is very high at the place

where system is deployed, it is good to have a shield around the twisted pair to ground the noise before they get coupled to the wires.

In summary following points should be taken care while using diodes for temperature measurement:

- Four wires measurement must be done with measurement wires connected to diode as close as possible.
- ADC must be calibrated for offset and gain error.
- DAC must be calibrated for gain error.
- Instead of standard two lead diode, diode connected transistor must be used.
- A transistor, which has fairly constant h_{FE} over collector current, must be used.
- To deal with high frequencies, twisted pair wires must be used. Shielding must be used if noise is very high.

Conclusion

Diodes being the most inexpensive are the potential candidates for low cost temperature measurement applications. This article talks about the points to be taken care, to make accurate measurement using them. SoCs offer higher integrations while implementing remote sensing diode applications as they have internal ADCs, DACs, multiplexer.

About the Authors

Sachin Gupta is a Senior Applications Engineer with Cypress Semiconductor. He loves working on different types of analog and digital circuits, as well as synthesizable codes. He can be reached at sgup@cypress.com.

Umanath Kamath works as an Applications Engineer with Cypress Semiconductors. He enjoys building analog and digital circuits and systems using different types of sensors.